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REPORT OF INVESTIGATIONS/1993

An Instrumented Pneumatic Backfilling System

By Robert C. Dyni

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cfm	cubic foot per minute	Ω	ohm
ft	foot	psig	pound (force) per square inch, gauge
ft/s	foot per second	s	second
h	hour	st	short ton
in	inch	V ac	volt, alternating current
lx	lux	V dc	volt, direct current
mm	millimeter	W	watt

AN INSTRUMENTED PNEUMATIC BACKFILLING SYSTEM

By Robert C. Dyni[1]

ABSTRACT

The use of techniques and equipment designed to pneumatically place backfill into an underground mine opening through boreholes for subsidence abatement has historically met with limited success, largely due to the inability to directly monitor the placement of the backfill in the opening. The success of a backfilling project cannot be guaranteed if it is not known whether the underground opening has been completely filled with backfill material.

To overcome the inability to directly monitor backfill placement, the U.S. Bureau of Mines developed a pneumatic backfilling system that allows for direct viewing of the backfill as it is placed in an underground mine opening. This system utilizes a recently developed pneumatic nozzle coupled with an instrumentation package that allows for real-time observations and measurements of backfill placed in an underground opening through a borehole.

The nozzle utilizes a high-velocity airstream to redirect backfill falling through a pipe in the borehole and directly in front of the nozzle; the airstream redirects and propels the backfill horizontally into the mine opening at over 100 ft/s. The instrumentation package, mounted directly to the nozzle, contains a video camera, high-intensity lamps, laser-rangefinder, electronic compass, and water sensor.

[1]Structural engineer, Pittsburgh Research Center, U.S. Bureau of Mines, Pittsburgh, PA.

INTRODUCTION

Pneumatic stowing has been demonstrated to be an effective method for backfilling mine voids. This method involves placing material into a mine opening using air pressure to transport the material through transport pipelines and into the mine opening. Since many abandoned mines are not directly accessible, borehole pneumatic backfilling techniques have been developed.[2] The use of remote pneumatic stowing methods for the purpose of backfilling voids for subsidence control, however, has been limited. The problems encountered during the operation of borehole pneumatic systems have been the inability to project material far from the injection borehole, the inability to directly monitor where the material is actually being placed (leading to incomplete void filling), and the high rate of wear and abrasion by the backfill material on the equipment.

In response to a need to improve the effectiveness and efficiency of remote pneumatic backfilling through boreholes, the U.S. Bureau of Mines developed an efficient, articulated pneumatic nozzle system that incorporates instrumentation for real-time monitoring and directional control of the backfilling process. This system consists of two major components. First, a high-efficiency, directional nozzle was developed to improve the efficiency and controllability of discharging backfill into a mine opening. Second, an instrumentation module, directly coupled to the nozzle, was designed and constructed to allow direct, real-time monitoring of the backfill process, and to provide information needed to better control and place backfill in a mine opening. This instrumentation module contains a complete video camera and lighting system, laser-rangefinder, compass, and water detection device.

The instrumented pneumatic backfill system was developed under the USBM's Abandoned Mine Land (AML) Research Program and was tested at the USBM's Subsidence Abatement Investigation Laboratory (SAIL).

SYSTEM DESCRIPTION

The pneumatic backfilling nozzle system was designed to provide a more effective means of overcoming the problems encountered in previous pneumatic backfilling systems. The most significant problem with previous remote backfilling systems was that the operator could not directly monitor the placement of backfill material. This resulted in incomplete filling of a mine entry and ineffective subsidence abatement treatments. The other significant problem with previous systems was high wear and limited throw distances. Previous pneumatic systems utilized thick wear plates where the backfill material delivery pipe bends at the bottom of the borehole, to maximize the useful life of the system.

To allow direct monitoring of the backfill process, the USBM's pneumatic nozzle system has several instruments that provide a variety of data useful for increasing the overall efficiency of a backfilling operation. The nozzle incorporates the use of supersonic airflow and eliminates high wear in the delivery pipes, which allows for higher efficiency, longer life, and longer throw distances from the nozzle. Figure 1 shows the major components of the instrumented nozzle system.

NOZZLE ASSEMBLY

In past pneumatic backfill system designs, the backfill material is delivered via high-velocity airflow through a pipe installed down a borehole. At the bottom of the borehole, the pipe must bend; an elbow or deflector is used to redirect the backfill material horizontally out the end of the pipe and into the mine opening. This type of system experiences high wear and abrasion at the elbow location, and has limited performance (fig. 2).

The nozzle developed under this project utilizes a design developed under a previous USBM study.[3] The previous nozzle design, known as the Burnett High-Efficiency Ejector, eliminates the wear problems and has greater performance. Backfill material is gravity fed through a pipe and is redirected at the bottom of the borehole by a flow of air traveling at supersonic velocity (fig. 3). The supersonic velocity of the airstream from the nozzle imparts horizontal momentum to the backfill material. The nozzle developed for this project was designed to further redirect the backfill material through a barrel as the backfill material exits the system (fig. 4). The nozzle barrel was designed to constrain the ejected backfill material to a single direction for increased directional control. Although the High-Efficiency Ejector has been demonstrated to perform successfully without a barrel, it

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[2]Burnett, M. Development and Testing of a Dry Feed Ejector for Backfilling Abandoned Underground Mines (OSMRE contract HQ51-GR87-10008, Burnett Eng.). OSMRE, 1988, 45 pp.

____. Development of a High-Efficiency Ejector System (contract J0309012, Burnett Eng.). BuMines OFR (in press), 1991, 31 pp.

Hanson, L. C. Design and Evaluation of a Remote Air-Jet Pneumatic Stowing System (contract J0388015, L. C. Hanson Co.). BuMines OFR (in press), 1990, 51 pp.

Masullo, A. L. Above-Ground Demonstration of Pneumatic Stowing Technologies (contract J0388012, ICF/SRW Assoc.). BuMines OFR 17-91, 1990, 75 pp.; NTIS PB 91-170142.

[3]Second work cited in footnote 2.

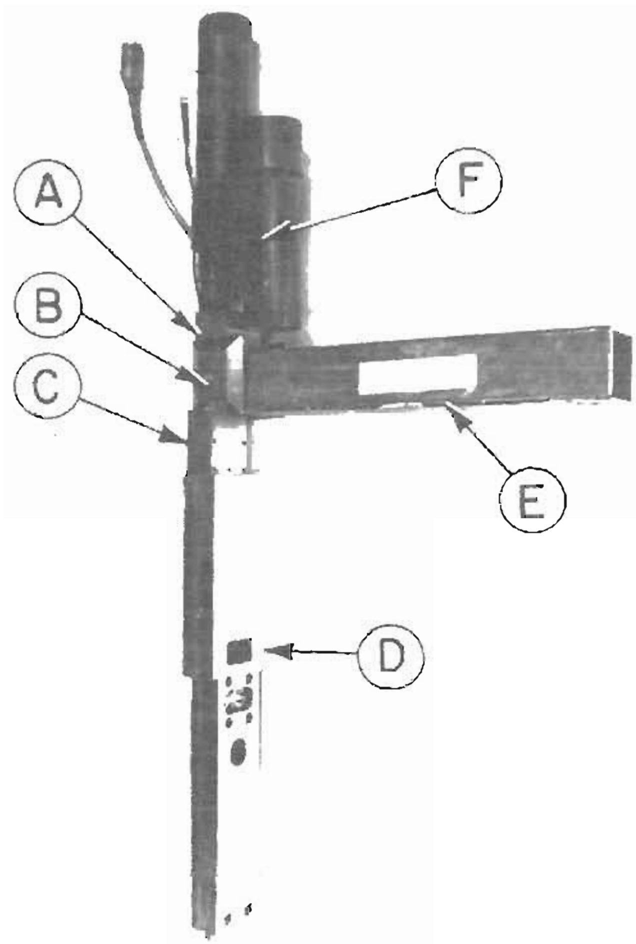

Figure 1.—Instrumented pneumatic backfilling system. A, Nozzle body; B, barrel attachment plates; C, adapter housing; D, instrumentation housing; E, barrel; and F, carrier assembly.

Figure 2.—Typical previous nozzle design.

was thought that a directional capability for placing the backfill material was a valid design change.

Nozzle Designs

The nozzle has several components that provide increased efficiency and reduced wear. Figure 5 shows the major components of the nozzle. The carrier assembly aligns the air delivery pipe and the backfill delivery pipe as shown in figures 1 and 5. The backfill delivery pipe is oriented so that backfill material falls directly in front of the supersonic airstream generated by a single nozzle.

The nozzle body, machined from a single bar of nonmagnetic stainless steel, contains the nozzle, which can be rotated ± 15° from the horizontal (fig. 5). The nozzle was also machined from nonmagnetic stainless steel, and is a convergent-divergent system that expands incoming air to supersonic velocity. Air delivered to the nozzle designed

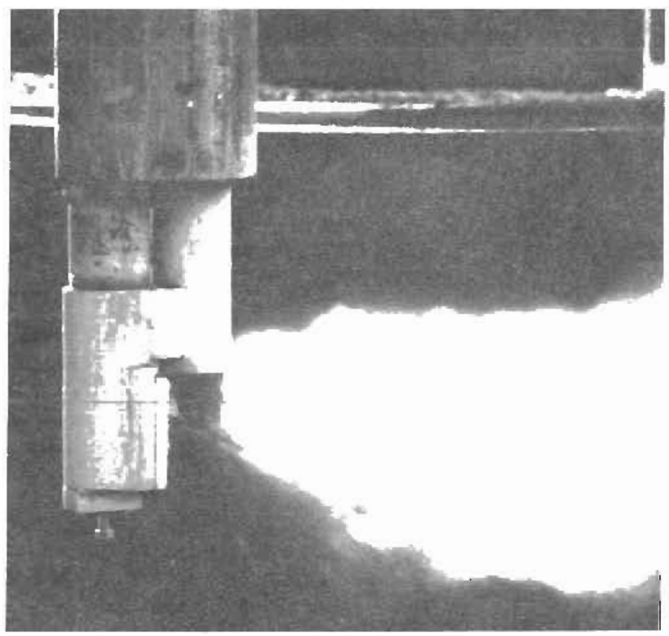

Figure 3.—High-Efficiency Ejector.

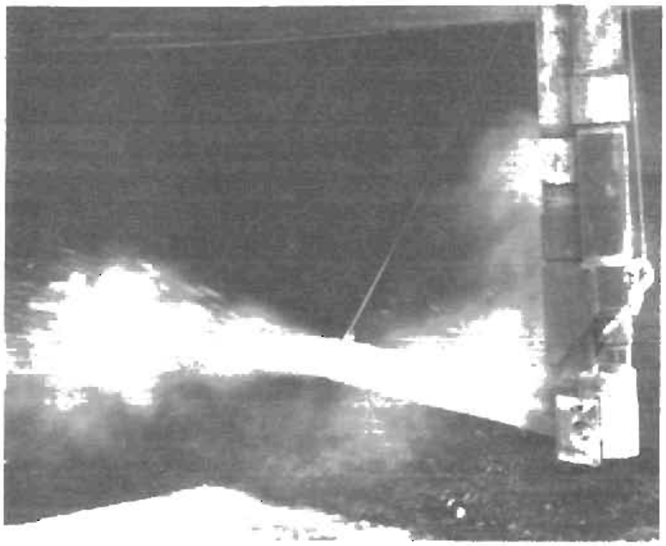

Figure 4.—Nozzle with barrel.

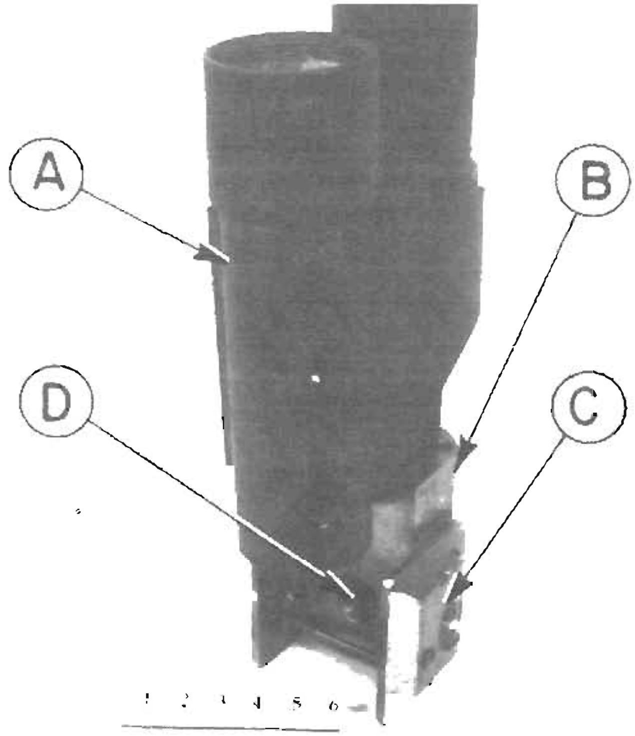

Figure 5.—Nozzle components. A, Carrier assembly; B, nozzle body; C, barrel attachment plates; and D, nozzle.

for this project is 1,250 cfm at 100 psig. A detailed explanation of the design and theory of the convergent-divergent nozzle is provided by Burnett.[4]

The nozzle body attaches to the carrier assembly with a threaded steel adapter pipe, which also transports air from the air supply pipe. Communication and power cabling from the ground surface to the downhole instrument package pass through two holes on either side of the nozzle body.

Barrel Designs

The nozzle barrel was designed to confine the ejected backfill material to a single direction; the design also allowed the barrel to be rotated ±15° to allow precise aiming and placement of backfill material. Two different barrels were designed; the first was a 3.5-in-OD, 30-in-long nonmagnetic stainless steel schedule 40 pipe (fig. 6), and the second was a 3-in square-sided, 24-in-long steel tube constructed of 0.25-in stainless steel plate, with a replaceable wear plate on the bottom inside surface (fig. 7).

The first nozzle barrel is shown in figure 6. The barrel hinge was machined from nonmagnetic stainless steel and was welded to the barrel pipe. This first barrel was designed to provide an inexpensive barrel that could easily be manufactured. Initial testing of this barrel design, however, indicated that wear associated with backfill material traveling through the pipe caused premature failure of the pipe; thus, the second barrel was designed to reduce this problem. The second nozzle barrel is shown in figure 7. The replaceable wear plate was constructed of 0.25-in stainless steel plate, and its top surface was coated with 0.25 in of a ceramic carbide wear- and abrasion-resistant material. The wear plate bolts to the bottom inside surface of the barrel.

The two barrels were designed to attach to the nozzle in such a way as to allow the barrel and nozzle to remain in alignment as the barrel is rotated ±15° from the nozzle's horizontal axis. Each barrel has an indent machined on each side that allows two locking pins to secure it to the nozzle's barrel attachment plates (fig. 5) when the barrel is brought up to its working position. The barrel is actuated from the ground surface by a cable; the barrel hangs vertically when lowered or raised through a borehole, and pulling on the cable swings the barrel up to a horizontal position and locks it into the nozzle body.

Support Equipment

There are several components required for the operation of the pneumatic nozzle. First, an air compressor is needed to supply the appropriate volume of air (1,250 cfm at 100 psig) to the nozzle. Second, a hopper mounted to the collar of the backfill material supply pipe is required to place the backfill material down the pipe (fig. 8). Third, a large bin or hopper with a belt or vibratory feeder

[4]Second work cited in footnote 2.

Burnett, M. Development of an Inexpensive Pneumatic Pipefeeder (contract J0388011, Burnett Eng.). BuMines OFR 13-91, 1990, 38 pp.; NTIS PB 91-170167.

is needed to supply the backfill material to the hopper on the collar of the material pipe (fig. 9).

The material used for testing at the SAIL was a 0.75-in topsize limestone. This material was stockpiled and was placed into the large hopper with a front-end loader. A variable-speed conveyor belt, equipped with an electronic belt scale, transferred material from the large hopper to the main tower conveyor belt (fig. 9). Using this scale, it was possible to monitor total tonnage of material stowed and the rate at which material was being delivered to the nozzle.

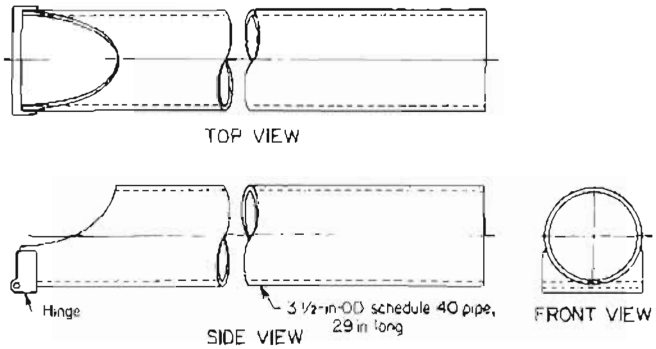

Figure 6.—First-generation barrel.

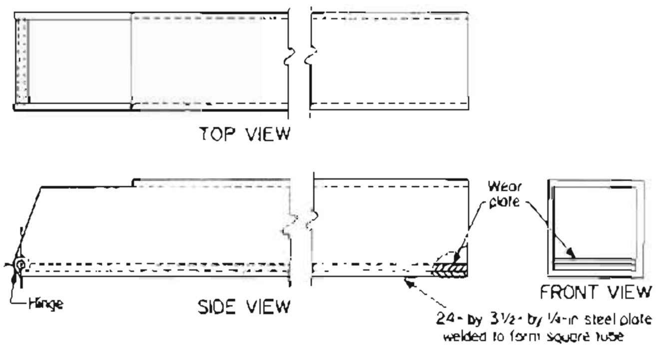

Figure 7.—Second-generation barrel.

INSTRUMENTATION SYSTEM

The instrumentation system consists of a video camera, lighting system, laser-rangefinder, compass, water sensor, and remote control center. The instruments, which provide qualitative and quantitative data on the size and distribution of backfill material, are operated from the remote control center.

The instrumentation system consists of two major components. First, the instrument housing provides a protective enclosure for all of the instruments, and second, the adapter housing provides a location for connection of all electrical and communications wiring from the instrument housing to the cable connected to the remote control center. The adapter housing also provides the physical link between the instrument housing and the nozzle body.

Instrumentation Housing

The instrument housing was constructed of nonmagnetic stainless steel and the housing cover was made from 4-in-OD schedule 40 nonmagnetic stainless steel pipe (figs. 1 and 10). The housing provides a sturdy enclosure for the instrumentation and protects the instruments from moisture and other contamination. The nonmagnetic stainless steel was specified so that magnetic interference from the housing to the instruments would be minimal.

The windows for the laser-rangefinder, lights, and video camera were constructed of various materials. The original design called for synthetic sapphire window material, but availability and cost did not allow for installation of

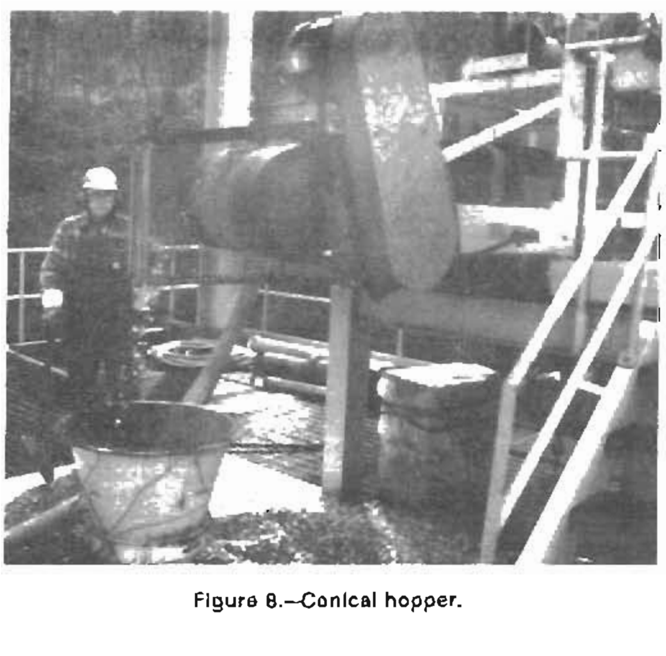

Figure 8.—Conical hopper.

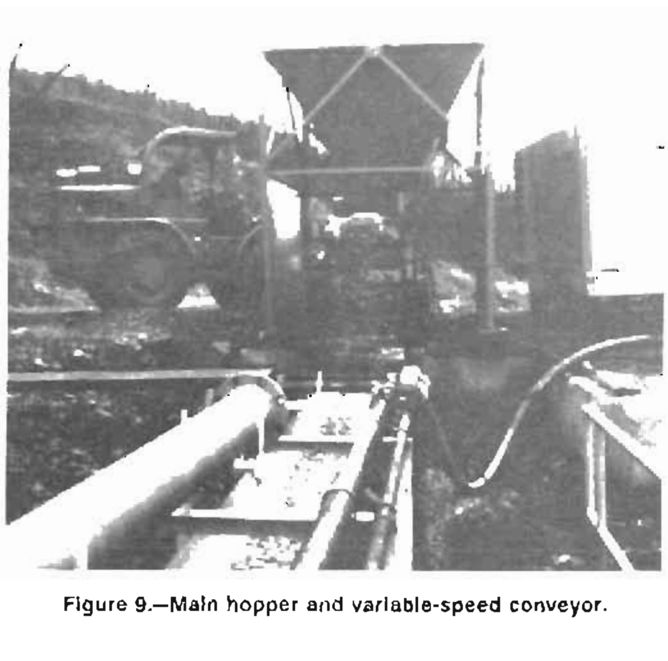

Figure 9.—Main hopper and variable-speed conveyor.

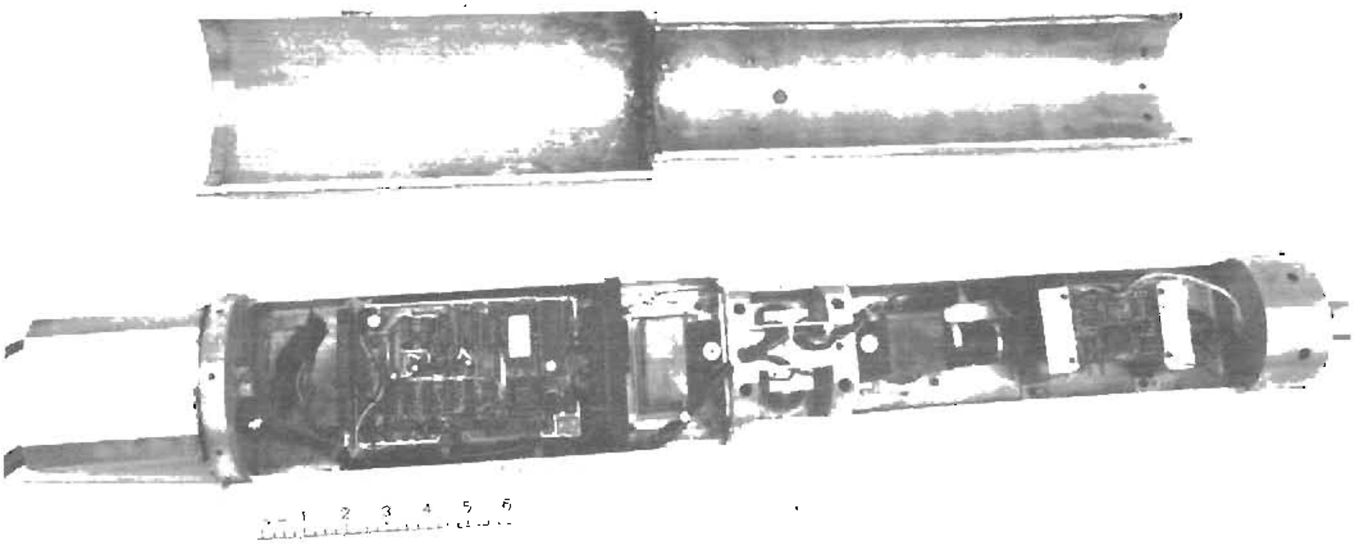

Figure 10.—Instrument housing, showing overall layout of internal instruments.

this material. Instead, the video and laser-rangefinder windows were constructed of 0.125-in-thick Type 9034 Lexan[5] sheet, and the light window was 0.25-in-thick Type A4009 heat-absorbing and infrared-blocking glass.

The adapter housing provides the link between the instrument housing and the nozzle body (figs. 1 and 10). This housing, machined from aluminum bar stock, provides room for wire connections between the instrument housing and the cable connecting the instrument system to the remote control system.

Video Camera

The video camera provides a means of visually inspecting a mine opening and monitoring the progression of backfill operations. This instrument is also extremely useful for determining overall mine conditions.

The video capability of the instrumentation system utilizes a miniature high-resolution monochrome cylindrical CCD (charge-coupled device) camera. The camera is capable of effectively operating with only 1 lx illumination. The camera body is approximately 2.6 in long and 1.1 in in diameter. The lens adds another 1.5 in to the camera's overall length. The camera is mounted into the instrument housing using a cradle and clamp. Figure 11 shows the location of the video camera in the instrument housing.

Focus and aperture of the lens must be manually controlled; therefore, focus is preset at infinity, and the lens aperture is set to the fully open configuration before insertion into the borehole to allow the maximum amount of light into the camera. It is anticipated that future refinements of the camera will include remote control capabilities for focus and aperture settings.

[5]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

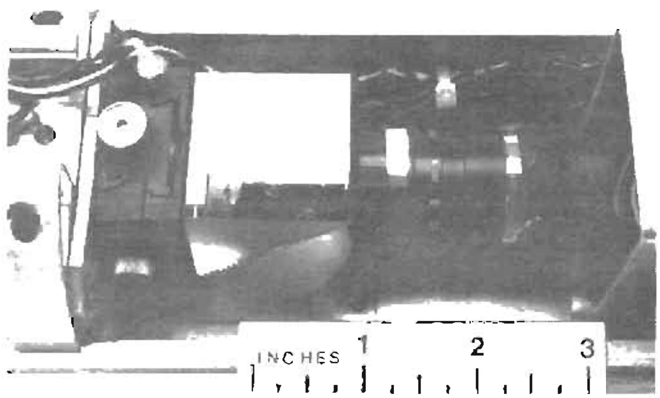

Figure 11.—Video camera mounted in instrumentation housing. Front-surface mirror, which is attached to goniometer, and access window are visible.

The camera is mounted with its longitudinal axis oriented along the length of the instrument housing. A front-surface mirror attached to a goniometer (fig. 11) allows for camera operation through the access window. The goniometer is also manually manipulated; future refinements will include motorized goniometers, allowing for remote manipulation of the mirror assembly.

Lighting System

The lighting system is designed to illuminate a mine opening for the video camera. Since the aperture of the camera is fixed, overexposure and underexposure of the video image can be controlled using the variable-intensity feature of the lighting system. The lighting system consists of two 35-W high-intensity quartz-halogen lamps wired in series. Figure 12 shows the installation of the lamps in the instrument housing.

Laser-Rangefinder

The laser-rangefinder measures the distance from the nozzle system to any feature within the mine opening. It is useful for determining the size of a mine opening before backfilling operations begin, and it is useful for measuring the size of the backfill pile and the distance from the nozzle to the backfill pile during backfilling operations. Used in conjunction with the video camera, overall dimensions of the mine opening and backfill pile can be obtained. The laser beam is aimed by moving the entire nozzle assembly; vertical orientation is manually set using an adjustable mirror attached to a goniometer within the instrument housing prior to insertion into a mine opening. The laser can be aimed by raising and lowering the entire nozzle and instrument assembly.

The laser-rangefinder is an electronic distance meter (EDM) that utilizes a visible, eye-safe solid-state laser. The rangefinder emits a beam of laser light that reflects off of a target surface (such as a backfill pile), and the reflected light is received by the instrument. The instrument then calculates the distance from the instrument to the target; accuracy of the measurement is reported to be ±0.2 in. A measurement taken with the laser-rangefinder typically takes 4 s. The range of the instrument is reported to be 100 ft.

The laser-rangefinder is an off-the-shelf instrument designed for surveying applications. The instrument was modified only to the extent of allowing the hardware to fit within the instrument housing. This instrument is equipped with an RS-232 communications cable that allows for operation from the remote control center via an RS-232-compatible terminal. Figure 13 shows the location of the laser-rangefinder in the instrumentation housing.

As with the video camera, the laser-rangefinder is oriented along the longitudinal axis of the instrument housing. Thus, a front-surface mirror mounted on an adjustable goniometer orients the laser beam and reflected signals through the window of the instrument housing. Manual adjustment of this goniometer is necessary, and future refinements to the system will include remote operation of the goniometer.

Electronic Compass

The compass is designed to provide information as to the nozzle's orientation within a mine opening. Since the nozzle is unseen from the surface, it is impossible to determine exactly where the nozzle is directed underground. As the pipe assembly is rotated on the surface, the same rotation may not be transmitted to the nozzle because of twisting of the pipes in the borehole; thus, the compass provides instant information regarding the horizontal bearing of the nozzle at all times.

The compass system is a magnetic heading sensor; it utilizes a gimballed sensor to ensure that the compass is exactly vertical whether or not the instrument housing is slanted or vertical. The compass itself is a state-of-the-art microprocessor-controlled fluxgate compass, consisting of a gimballed toroidal fluxgate sensing element and a small electronics board. The sensor takes 10 measurements of the Earth's magnetic field every second. The signals are analyzed by the onboard microprocessor, and the resulting data are sent via cabling to the remote control center on the surface. Figure 14 shows the compass installed in the instrumentation housing.

Water Sensor

The water sensor is designed to warn of the presence of flooded conditions in an underground environment so that the instrumentation housing will not be inadvertently submerged and damaged. The electrolytic-type sensor consists of two copper wire conductors situated at the bottom of the instrument housing. If the two conductors are simultaneously submerged in water, a current flows between them via electrolytic action; this current flow can trigger a visual or audio alarm system, thereby alerting the

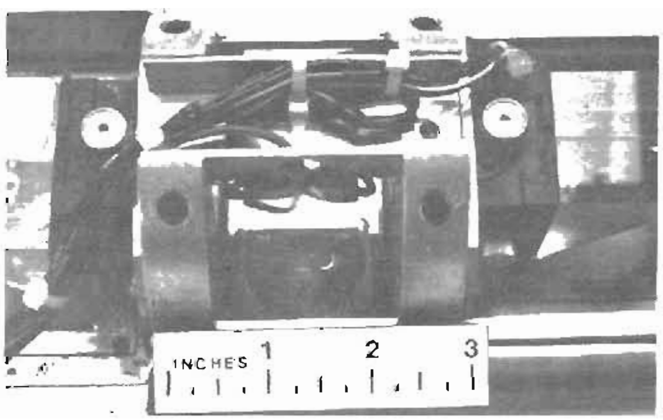

Figure 12.—High-intensity lamps mounted in instrumentation housing.

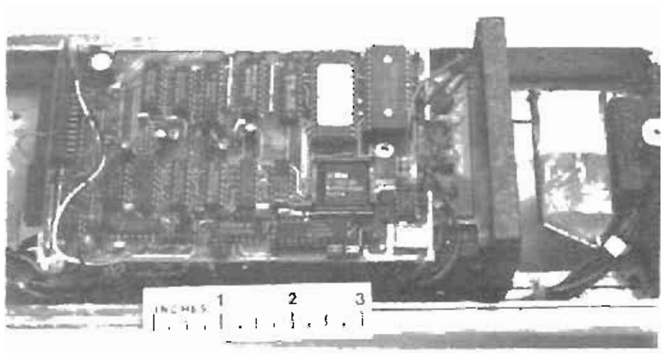

Figure 13.—Laser-rangefinder mounted in instrumentation housing. Front-surface mirror attached to goniometer is visible at right.

operator of flooded mine conditions. Figure 15 shows the water sensor installed at the bottom of the instrument housing.

Remote Control Center

The remote control center provides all power and control functions to the instruments at the nozzle location. The control center contains separate power supplies for all instruments in the instrumentation system. Each instrument also requires one or more operational controls; these controls are located on the master control panel of the remote control center. All of the instruments require direct power and communications wiring from the nozzle location to the remote control center; a 200-ft-long, 24-wire shielded cable was used to provide the direct link between the remote control center and the instrument housing.

The components of the control center are mounted in a rugged, shock-resistant box (fig. 16) so that the entire system can be transported to any location without difficulty. The communications and power cabling from the nozzle assembly plug into the back of the box along with the 120-V ac power source.

The laser-rangefinder power requirements are met with a 7.5-V dc power supply located in the remote control center. The control of the laser-rangefinder, including power on-off, measurement triggering, and data collection, is handled by a controller unit connected to an RS-232 plug on the master control panel (fig. 16).

The video camera is powered by a 12-V dc power supply. An on-off switch located on the master control panel is the only control necessary for the operation of the camera (fig. 16). A separate 75-Ω shielded coaxial cable was used to transmit the video image from the camera to the remote control center, while the main 24-wire cable

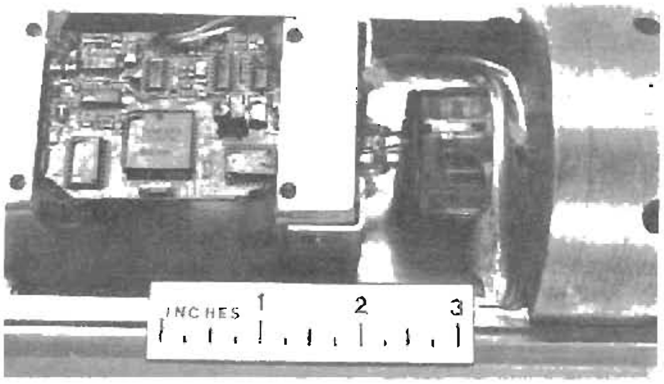

Figure 14.—Electronic compass mounted in instrumentation housing.

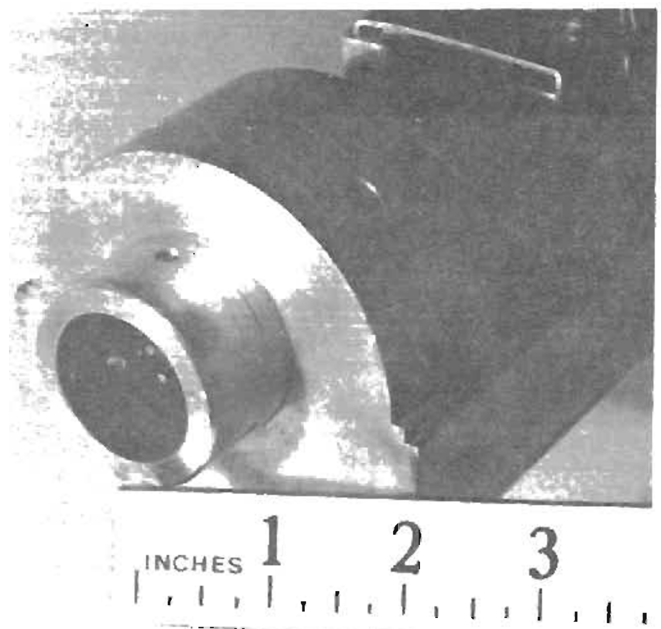

Figure 15.—Water sensor mounted on bottom of instrumentation housing.

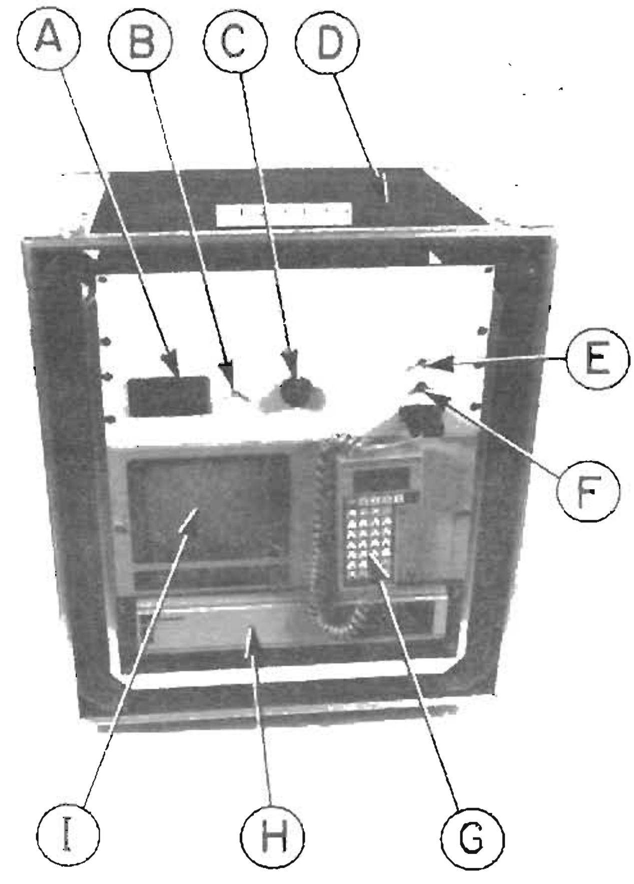

Figure 16.—Front view of remote control center. A, Digital compass readout panel meter; B, video camera on-off switch; C, variable-intensity rheostat; D, shock-resistant box; E, water sensor on-off switch; F, water sensor indication light; G, laser-rangefinder controller unit; H, time-lapse video tape recorder; and I, video display screen.

was used for powering the camera. A video display screen is rack mounted in the control center for real-time viewing of the mine environment (fig. 16).

The lighting system is powered by a variable 24-V dc power supply. A variable-intensity rheostat is mounted on the master control panel (fig. 16).

The compass is powered by an on-off switch; this switch and an indication light are mounted on the master control panel (fig. 16). The compass requires no direct control; a digital readout panel meter is mounted on the master control panel (fig. 16). The compass is fully powered at all times. The water sensor is powered by a 12-V dc power supply (fig. 16).

The control center also houses a video tape recorder (fig. 16). A taped record of all observations made with the video camera is possible with this unit. This unit also has a time-lapse function, which allows hours worth of backfilling operations to be condensed into several minutes or less.

SYSTEM TEST PROGRAM

The instrumented nozzle system was field tested at the SAIL. The SAIL is located at the USBM's Lake Lynn Laboratory near Fairchance, PA. The SAIL provides a unique and flexible environment for evaluating the performance and effectiveness of a wide range of subsidence mitigation technologies. The SAIL is designed to simulate a borehole extending from the ground surface down to an abandoned underground mine opening; the design is flexible, allowing for differing borehole configurations as well as differing mine geometries. Thus, any subsidence abatement technology that utilizes boreholes for the installation of artificial support can be effectively tested and evaluated at the SAIL.

The SAIL configuration, as illustrated in figure 17, has been established to simulate remote backfilling in a typical coal mine. With modifications, the laboratory can be configured to a number of different conditions, including open stopes, tunnels, and flooded mines.

The intent of the testing program was to demonstrate the capabilities of each component of the instrumented pneumatic nozzle system under realistic abandoned underground mine conditions. Thus, a simulated coal mine entry was constructed; the walls or ribs of the entry are constructed of 2-ft-high, 2-ft-wide, 6-ft-long concrete blocks, and the mine roof is constructed of steel bridge planking. This planking can be removed from the opening

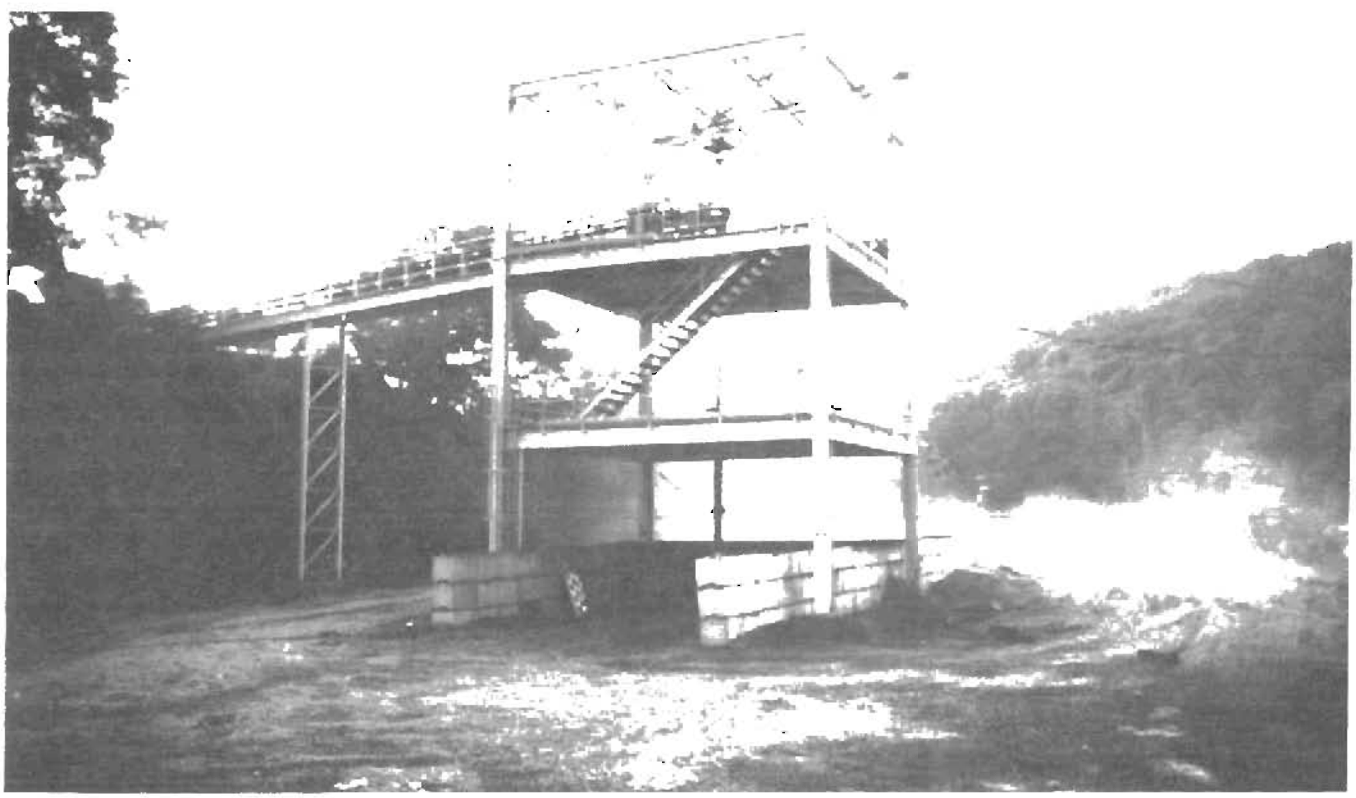

Figure 17.—Subsidence Abatement Investigation Laboratory.

to evaluate and observe a backfill pile. For the instrumented nozzle tests, total length of the mine entry was approximately 85 ft from the borehole location to the far end of the entry, the width was 20 ft, and the height was 6 ft.

INSTRUMENT TESTS

The instrument housing was installed on both the USBM nozzle with barrel and the Burnett High-Efficiency Ejector (figs. 18-19). Each instrument contained in the instrument housing was individually tested to determine its operation and overall effectiveness. Since testing was performed at the SAIL, which is located outdoors, the video testing program was performed at night to provide the closest possible simulation of an abandoned underground mine.

Video System

The video camera and the high-intensity lights were tested in total darkness at the SAIL to provide information as to the overall range of both the camera and lighting system. A series of high-contrast targets were hung from the roof of the simulated mine at 10-ft increments starting 10 ft from the nozzle and ending 80 ft from the nozzle, at the far end of the entry. Each target had a checkerboard pattern of alternating 6-in by 6-in black and white squares. By using these targets, an accurate determination was made of the camera's effective sight distance.

During the camera tests, two different lenses were evaluated. The first lens tested was a 6.5-mm, f1:1.8 wide-angle lens with adjustable aperture and infinite focus, and the second lens was a 50-mm, f1:2.8 lens with adjustable aperture and focus. The first lens had an aperture range of f1.8 through f16, and the second lens had an aperture range of f2.8 through f16. For the tests, both lens apertures were set on the lowest f-stop, which equated to the widest lens opening and therefore the greatest light-gathering capability.

The results of the video tests demonstrated the superior light-gathering capabilities of the camera. The camera installed with the 6.5-mm lens provided a wide field of view of the mine opening. The wide-angle capabilities of this lens were so great that a portion of the interior of the instrument housing was visible. The entire 20-ft width of the mine entry was visible at approximately 20 ft from the nozzle location, and the 6-ft height of the entry was visible from 10 to 85 ft. All targets were clearly visible.

The camera installed with the 50-mm lens provided a narrow field of view, yet provided a sharp image of all targets. The entire 20-ft width of the mine entry was visible at approximately 80 ft from the nozzle location, and the full height of the mine entry was visible at approximately 50 ft. The image, although clear, was somewhat darker than the image obtained by the wide-angle lens.

Each lens tested had unique advantages and disadvantages. The 6.5-mm lens was able to provide a very wide field of view, which meant that a complete video image of the mine entry was possible without having to rotate either the internal mirror or the instrument housing to obtain a complete image. The lens also allowed for an extremely bright and clear image. However, the wide-angle capabilities of the lens limited the resolution, or detail, of the image. The 50-mm lens, on the other hand, provided a much more detailed image, but drastically limited the field

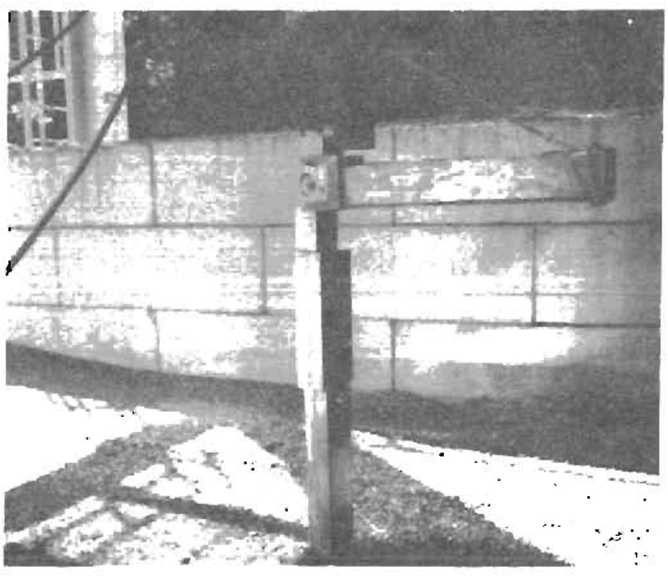

Figure 18.—Instrument housing mated to nozzle with barrel.

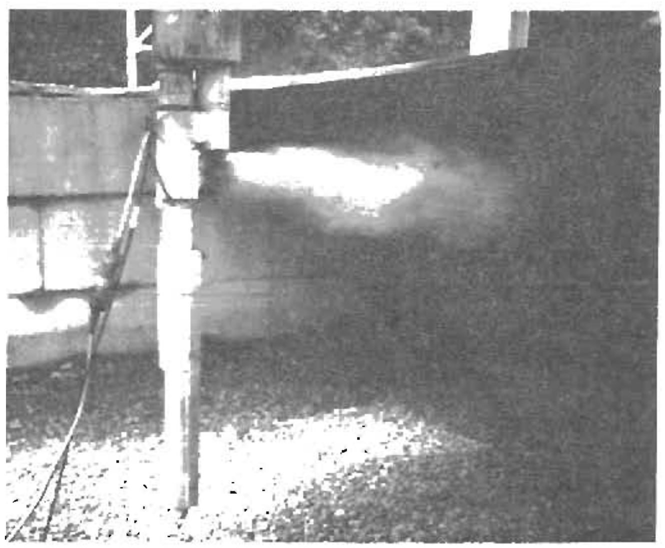

Figure 19.—Instrument housing mated to High-Efficiency Ejector.

of view, and a complete image of the mine opening was not possible without rotating either the internal mirror or the instrument housing. Both lenses required manual adjustments for proper focus of nearby objects, but this was not required for objects farther than 10 to 20 ft from the nozzle location.

The high-intensity lamps provided sufficient illumination for both lenses tested. The variable-intensity capability of the lamps provided a means to control over- or underexposure of the video images. However, the thermal glass used as the window for the lamps proved to be sensitive to the high temperatures generated by the lamps; the glass cracked within 1 h after starting the tests of the video system. During the test, the lamps were repeatedly cycled from dim to bright illumination; the temperature fluctuations associated with this cycling of the lamps ultimately cracked the glass.

Another problem that was discovered during testing of the video system was that condensation formed on the interior surface of the video camera window. Apparently, moisture trapped in the housing condensed as the internal temperature of the housing increased, causing an internal fogging of the window. This problem was countered by adding a desiccant canister to the housing interior.

Laser-Rangefinder

The laser-rangefinder was tested to determine its overall range using both a white target and actual backfill material as reflective surfaces. For the target test, the target was placed at 10-ft intervals starting at 10 ft from the instrumentation housing and ending at the 80-ft level. At the conclusion of the target test, a pile of backfill material was placed at 10-ft intervals starting at 10 ft from the instrumentation housing and ending at the 80-ft level. Ten measurements were taken at each target or backfill pile location. Table 1 shows the results of these tests.

The tests were performed in the following manner. For the target tests, the target was initially set at 10 ft from the instrument housing and a reading was made. The target was then moved back 10 ft and another reading was made. This procedure was repeated until the target reached the far end of the mine at the 80-ft level. The backfill pile tests were conducted in a similar manner.

As shown in table 1, the laser-rangefinder did not perform satisfactorily. The measurements made using the white targets were largely obtainable, although some problems were encountered. The effective range of the laser-rangefinder with the white targets was 70 ft. However, the measurements made using the backfill piles were very poor; the overall range of the instrument when measuring the piles was only 30 ft, and even distances less than these limits were difficult to obtain. The major problem was that while the rangefinder unit was apparently often able to detect a return signal off of the targets or backfill piles, the electronics were unable to relay the proper information back to the remote control station. It was also found that the laser-rangefinder was unable to detect return signals off of the backfill piles beyond 40 ft.

Table 1.—Laser-rangefinder test results, feet

Distance from nozzle	Rangefinder readout	
	White target	Backfill
10	9.42	3.90[1]
20	6.00[1]	6.5?[1,2]
30	30.42[2,3]	9.6?[1,2]
40	39.75[3]	??.00[1,2]
50	50.42[3]	([4])
60	59.00	([4])
70	69.50[3]	([4])
80	?9.42[2]	([4])
85	?5.0?[2]	([4])

[1]Readout of measurement in U.S. customary units was not possible. The laser-rangefinder was instructed to provide readout in metric units.

[2]Laser-rangefinder received a return signal, but readout dropped a digit from the display.

[3]Target was moved back or forth several inches, and measurement was retaken to obtain reading.

[4]No return signal.

Two other problems were encountered during the laser-rangefinder tests. As in the video tests, condensation formed on the Lexan window, prohibiting the transmission of the laser beam to the desired targets. This problem was countered by the addition of the desiccant canister. Another problem was the lack of vertical control for aiming the laser beam. Aiming of the beam in the horizontal plane was accomplished by rotating the entire instrument housing, but aiming in the vertical plane was impossible without manually controlling the goniometer that held the front-surface aiming mirror.

The wavelength of the laser beam is in the red portion of the visible spectrum; the beam was clearly visible in the video images where the beam reflected off a solid surface.

Electronic Compass

The electronic compass was tested to determine its effectiveness and operation. Since the compass required no manual input or other operation, testing of the instrument only involved rotating the instrument housing and monitoring the digital compass readout at the remote control center.

The compass performed as expected, and with no apparent difficulties. There was concern that the compass might be influenced by interference from the other instruments in the housing, or by the housing itself, but this was not the case. The compass continually tracked the proper orientation of the nozzle assembly with no disruptions.

Water Sensor

The water sensor was tested by simply submerging the bottom of the instrument housing in a container of water to determine the sensitivity and effectiveness of the unit. The water sensor performed as expected and with no apparent difficulties.

NOZZLE TESTS

The nozzle was tested at the SAIL to demonstrate the overall efficiency and durability of the nozzle components. The effectiveness of using convergent-divergent nozzles has been demonstrated in the Burnett High-Efficiency Ejector,[6] so extensive testing of the nozzle efficiency and resulting characteristics of the backfill was not planned. However, since this nozzle incorporated a barrel to direct the backfill material, which is an innovation not found on the High-Efficiency Ejector, the bulk of nozzle testing was designed to evaluate the performance of the barrel.

USBM-Designed Nozzle With Barrel

Initial tests of the nozzle and the first barrel design indicated that the barrel was wearing prematurely. Approximately 10 st of backfill material was ejected into the simulated mine opening before failure of the barrel occurred. The shape and location of the worn area suggests that the backfill material entering the barrel causes wear in two ways. First, the downward momentum of the material as it passes into the nozzle assembly creates large impact forces on the barrel. Second, the backfill material has no horizontal velocity as it enters the nozzle assembly, but upon entering the supersonic airstream the material is accelerated to 100 to 200 ft/s within the length of the barrel. This acceleration of the material creates large shear or frictional forces on the barrel. Thus, the combined normal and shear forces resulting from the redirection of backfill material through the nozzle assembly is much greater than the material strength of the nozzle barrel. Figure 20 shows the damage caused by excessive wear to the first barrel.

The second barrel was designed to reduce the effects of wear. This barrel incorporated a replaceable wear plate coated with a ceramic carbide abrasion-resistant material. With this design, the wear plate could be replaced when sufficiently worn without having to manufacture a new barrel. Unfortunately, testing showed that the ceramic carbide wear material could not withstand the tremendous impact and abrasion caused by the backfill material. Approximately 5 st of backfill was stowed before complete failure of the ceramic carbide wear material occurred. Figure 21 shows the wear of the failed wear plate as compared with an unused wear plate.

High-Efficiency Ejector

Since the nozzle and barrel combination was demonstrated to be unacceptable, a decision was made to couple the instrument housing to the Burnett High-Efficiency Ejector. As the purpose of the project was to provide an efficient, low-wear pneumatic backfilling system capable of monitoring the backfill process in real time, it was decided to couple the instrumentation to a previously proven nozzle design. Utilizing the USBM's single-nozzle design without the barrel would have proven to be extremely ineffective, since only one nozzle would have been available to redirect the backfill material delivered from the material delivery pipe. The Burnett High-Efficiency Ejector, on the other hand, utilizes five nozzles in which to redirect backfill material.

The Burnett High-Efficiency Ejector is shown in figures 3 and 19. Since this pneumatic backfilling device has been previously tested,[7] the objective was to only establish the compatibility of the ejector with the instrumentation housing, and to determine if vibrations or other stresses

[6]Second work cited in footnote 2.

[7]First work cited in footnote 2.

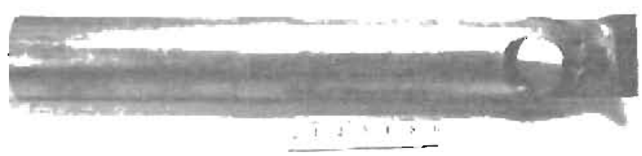

Figure 20.—Wear of first-generation barrel.

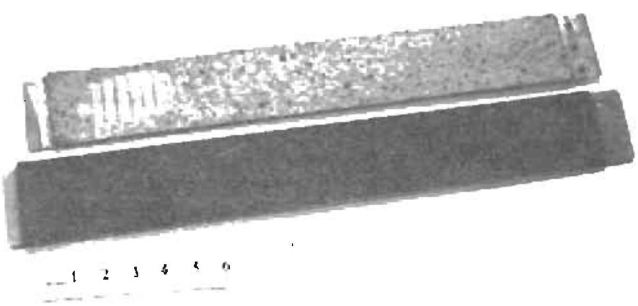

Figure 21.—Wear of second-generation barrel wear plate, compared with unused wear plate.

created by operating the system would affect the operation or performance of the instruments.

Figure 22 shows the external condition of the instrumentation housing after operation of the backfilling system for approximately 8 h. The most significant impact on the housing as a result of backfilling operations was the accumulation of debris on the video, light, and laser-rangefinder windows. Even though backfill material was ejected away from the instrumentation housing, water on the backfill material and in the air supply to the nozzle combined with the dust generated by backfilling to form a muddy deposit on the front face of the instrument housing. This deposit was thick enough to prevent the use of the video system, lights, and laser-rangefinder.

The instruments contained in the instrument housing all survived the operation of the nozzle without any apparent damage or fatigue. Each instrument was individually operated and tested, and all performed as well as before backfilling began. Very little vibration resulting from backfilling could be detected by physically touching the nozzle during operation. A rubber gasket between the adapter housing and the nozzle body served not only to provide a moisture-proof seal between the two components, but also served to dampen any vibrations generated from backfilling operations.

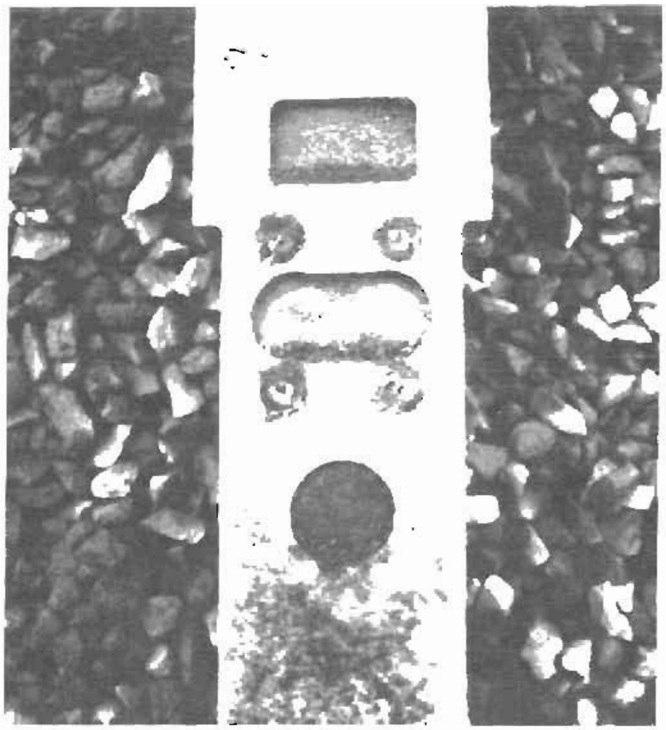

Figure 22.—Instrument housing after testing of nozzle assembly.

CONCLUSIONS AND RECOMMENDATIONS

The development of an instrumented pneumatic backfilling system clearly advances the state of the art in pneumatic backfilling technology. The capability to determine the orientation of a pneumatic nozzle and to monitor the placement of backfill from the nozzle location are two distinct advancements to the current state of the art.

The instrumented pneumatic nozzle developed under this research effort performed well, but several problems emerged that must be addressed before the system can be considered a viable backfilling device. Below are discussions on the overall effectiveness of the individual components of the system and the areas where additional work is necessary to improve overall effectiveness.

Laser-Rangefinder: The most significant problem encountered in the development of the instrumented pneumatic backfilling system was that of the laser-rangefinder. The instrument performance was less than satisfactory, in that the instrument was unable to successfully measure distances from the nozzle location to objects within the mine opening. This instrument could obtain accurate distance readings on reflective targets, but was clearly unable to obtain distance measurements to nonreflective targets such as backfill material in the mine opening. Additionally, the instrument had difficulty in transmitting readings back to the remote control center. Additional research is needed to determine the origin of these shortcomings, and to modify or redesign the instrument or communication link between the instrument and the remote control center.

Another significant problem with the laser-rangefinder involved the mirror that oriented the transmitted and reflected laser light through the instrument housing. Directional control of the laser is achievable only by rotating, raising, or lowering the instrument housing; rotation is easily accomplished from the surface, but vertical adjustment is more difficult. Motorizing the goniometer that holds the mirror would allow for remote vertical control of the laser beam, resulting in a more effective means of obtaining distance information to any point within the mine opening.

Video System: The video system performed extremely well. The low-light capabilities of the camera were ideally suited to underground mine environments. There were, however, several problems associated with the video system that must be addressed. First, the two lenses tested both revealed that the resulting images were not ideal for the task of monitoring the progression of a backfill pile, or for evaluating underground mine conditions. The 6.5-mm lens proved to obtain images that showed too wide an angle; the wide-angle feature of this lens was such that a portion of the interior of the housing around the video window was visible. Although the lens provided for a very large portion of the mine opening to be seen, this view lacked the detail and definition obtainable by the longer length lens. On the other hand, the 50-mm lens provided an image that was too narrow; only portions of the mine opening were visible, and to obtain a view of the entire opening either the camera mirror had to be rotated or the nozzle had to be vertically repositioned. It is thus clear that a lens is needed for the video system whose performance lies somewhere between the performance characteristics of the two lenses tested. Future work should involve optimizing the video system by selecting the most appropriate lens size.

Another problem encountered with the video system was that of a lack of focus or aperture control. Although this did not present any type of real operational deficiency, the remote control of these two parameters would provide an operator with the capability of adjusting the video image to its most viewable setting. Such control could be realized by motorizing the focus and aperture rings on the lens barrel; directional control of the motors would easily be achieved, and could be operated from the remote control center. Motorizing the goniometer that holds the video camera mirror could further enhance the capabilities of the video system by allowing the operator to remotely control the viewing direction of the camera.

The lighting system demonstrated that the lamps used were supplying enough illumination to the mine environment to allow effective use of the video camera. However, the lamps generated high temperatures that ultimately cracked the lamp window glass. The housing provided for no air circulation or other means of reducing the high temperatures at the window location. It is clear that some type of air circulation or cooling system is needed to reduce the high temperatures at the window glass. Such a system need not be highly sophisticated, but must be able to effectively reduce the temperatures to which the window glass is exposed. Alternatively, a different window material may be chosen that can more effectively deal with the high temperatures developed by the lamps.

Instrument Housing: The instrument housing proved to be a satisfactory enclosure for the instrumentation. The housing was rugged and capable of keeping harmful dust and water generated by the backfilling operations from the instruments. However, several problems were encountered during testing.

First, when the housing cover was sealed to the housing body for testing, internal moisture condensed onto the interior components, including the instruments as well as the windows. This problem, although serious, was countered by placing desiccant in the housing before sealing. A desiccant canister should be a mandatory item for the instrumentation housing, and protective coatings of plastic or other suitable material should be considered for protecting sensitive electronic circuit boards.

A second problem with the housing involved the accumulation of dirt and mud generated by the water and gravel being backfilled into the mine opening. The dirt and mud accumulated on all of the windows of the instrumentation housing, rendering impossible the successful operation of the video and laser-rangefinder systems. The addition of some type of air jet or water spray to the exterior of the housing could solve this problem. A high-pressure air or water curtain aimed directly at each window could keep the windows free from any contamination. A water spray would require additional piping from the surface to the instrument housing, and high-pressure air could simply be tapped from the air supply to the nozzle. A further protection could be obtained by constructing an awning or protective ledge above each window or above the entire instrument housing to further reduce the possibility of water and mud from contacting the exterior window surfaces, but clearance between such devices and the sides of a borehole could limit the size and ultimately the efficiency of such devices.

Nozzle: The supersonic nozzle was previously demonstrated to be capable of successfully stowing backfill material into a mine void. The nozzle assembly designed for this project, however, demonstrated that the addition of a nozzle barrel is detrimental to the operational life of the nozzle system. Although the addition of a barrel provides a higher degree of directional control, severe wear problems prohibited its use. While the barrels proved to be unsuccessful in that they wore quickly, the performance of the USBM's nozzle with barrel matched the tonnage rates of the High-Efficiency Ejector. Also, the barrels successfully provided for a highly directional dispersal of backfill material, which allowed for precise control of the backfilling process. Thus, since the concept of a nozzle barrel is a valid design consideration, any further investigation should include an attempt at developing a barrel that can withstand the tremendous forces exerted by the rapidly accelerating backfill material as it travels through the barrel.

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